

# ACCURATE SPECTRAL ENERGY DISTRIBUTIONS AND SELECTION EFFECTS FOR HIGH-REDSHIFT DUSTY GALAXIES: A NEW HOT POPULATION TO DISCOVER WITH THE *SPITZER SPACE TELESCOPE*?

A. W. BLAIN AND S. C. CHAPMAN  
Caltech, Pasadena, CA 91125

IAN SMAIL  
Institute for Computational Cosmology, University of Durham, Durham, UK

AND  
ROB IVISON<sup>1</sup>  
UK-ATC, Royal Observatory, Blackford Hill, Edinburgh, UK  
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## ABSTRACT

The spectral energy distributions (SEDs) of dust-enshrouded galaxies with powerful restframe far-infrared (IR) emission have been constrained by a range of ground-based and space-borne surveys. The *IRAS* catalog provides a reasonably complete picture of the dust emission from nearby galaxies (redshift  $z \simeq 0.1$ ) that are typically less luminous than about  $10^{12} L_{\odot}$ . However, at higher redshifts, the observational coverage from all existing far-IR and submillimeter surveys is much less complete. Here we investigate the SEDs of a new sample of high-redshift submillimeter-selected galaxies (SMGs), for which redshifts are known, allowing us to estimate reliable luminosities and characteristic dust temperatures. We demonstrate that a wide range of SEDs is present in the population, and that a substantial number of luminous dusty galaxies with hotter dust temperatures could exist at similar redshifts ( $z \simeq 2 - 3$ ), but remain undetected in existing submillimeter surveys. These hotter galaxies could be responsible for about a third of the extragalactic IR background radiation at a wavelength of about  $100 \mu\text{m}$ . The brightest of these galaxies would have far-IR luminosities of the order of  $10^{13} L_{\odot}$  and dust temperatures of the order of 60 K. Galaxies up to an order of magnitude less luminous with similar SEDs will be easy to detect and identify in the deepest *Spitzer Space Telescope* observations of extragalactic fields at  $24 \mu\text{m}$ .

*Subject headings:* galaxies: evolution – methods: observational – galaxies: interstellar medium – galaxies: starburst – cosmology: observations

## 1. INTRODUCTION

Deep submillimeter-wave surveys for distant galaxies offer direct access to high redshifts, because their sensitivity is almost independent of galaxy luminosity for a fixed spectral energy distribution (SED) over the wide redshift range  $1 < z < 5$  (Smail et al. 2002). The positional accuracy of these surveys is only  $\simeq 8$  arcsec, and optical counterparts are typically faint. Hence it has been difficult to identify and measure the redshifts of a substantial fraction of these submillimeter-selected galaxies (SMGs).

These difficulties have now been overcome with rest-UV spectroscopy of SMGs located in very deep ( $\simeq 10 \mu\text{Jy}$ ) radio images by Chapman et al. (2003b; 2004a). Redshifts have been found for about half of the SMG population using the Keck I telescope's blue-sensitive multiobject spectrograph LRIS-B. The resulting sample of 73 spectroscopic redshifts is very valuable, allowing a fairly accurate restframe SED to be determined for each galaxy, under reasonable assumptions about their radio-far-IR properties. The SED model is most strongly affected by the value of the effective dust temperature of the galaxies  $T_d$ , which can be treated as a proxy for the

peak restframe wavelength of the SED. Just two parameters,  $T_d$  and the far-IR luminosity  $L^2$  allow the parameter space of SEDs that describe observational data at wavelengths longer than about  $20 \mu\text{m}$  to be spanned reasonably well (Dale et al. 2001; Blain, Barnard & Chapman 2003; hereafter BBC03). Two other parameters are required to describe the detailed shape of the SED. The Rayleigh–Jeans spectral slope of dust emission is fixed by the emissivity index of dust  $\beta$  ( $f_{\nu} \propto \nu^{2+\beta}$ ). The value of  $\beta$  is degenerate with temperature, in the sense that models in which  $T_d\beta$  is approximately constant provide similarly accurate descriptions of the SED (see Fig. 2 of BBC03). This effect could be important if  $T_d$  were treated as a real physical temperature, but when  $T_d$  is used as the key descriptive parameter in the SED the effect of this degeneracy between the fitted values of  $T_d$  and  $\beta$  is not important. The slope of the mid-IR spectrum  $f_{\nu} \propto \nu^{\alpha}$  is set by a second parameter, which has little effect on the value of  $L$  at fixed  $T_d$ .

Spectroscopic redshifts are especially important for understanding the SEDs of SMGs as there is a very significant, pernicious degeneracy between the inferred dust temperature  $T_d$  and redshift  $z$ , which only allows accurate measurement of the quantity  $T_d/(1+z)$  (Blain

<sup>1</sup> Institute for Astronomy, University of Edinburgh, Blackford Hill, Edinburgh, UK

<sup>2</sup> Defined as the luminosity between wavelengths of 3 mm and  $10 \mu\text{m}$ , and typically close to the bolometric luminosity.

1999; BBC03). The large Chapman et al. sample of secure spectroscopic redshifts for SMGs provides a way to break this degeneracy, and thus unambiguously reveals the range of SED properties of the high-redshift population of SMGs. This is the population of galaxies for which radio–submillimeter–far-IR photometric redshifts are often sought (Carilli & Yun 1998; Hughes et al. 2002; Yun & Carilli 2002; Aretxaga et al. 2003; Wiklind 2003), and we use this new, accurate SED information, to address the precision of these radio–far-IR photometric redshift techniques. We then compare the SEDs of low- and high-redshift samples of luminous dusty galaxies to highlight a region of the  $L$ – $T_d$  parameter space where unrecognized populations could still lurk, and discuss ways to find them.

Throughout this paper we assume a cosmology with  $\Omega_0 = 0.3$ ,  $\Omega_\Lambda = 0.7$  and  $H_0 = 100 h \text{ km s}^{-1} \text{ Mpc}^{-1}$  with  $h = 0.65$  to remain consistent with earlier work. In the *WMAP* cosmology with  $\Omega_0 = 0.27$ ,  $\Omega_\Lambda = 0.73$  and  $h = 0.71$  the quoted luminosities would be reduced by a factor of about 15% at  $z \simeq 2.5$ .

## 2. LUMINOSITIES AND TEMPERATURES OF DUST-ENSHROUDED GALAXIES

In Fig. 1 we show values of inferred dust temperature  $T_d$  and bolometric far-IR luminosity  $L$  for several samples of dust-enshrouded galaxies. These include well-studied low-redshift *IRAS* galaxies with submillimeter measurements (Dunne et al. 2000; Dunne & Eales 2001), moderate-redshift galaxies selected jointly from the *IRAS* and the VLA-FIRST survey (Stanford et al. 2000) and high-redshift galaxies selected using both *Infrared Space Observatory* (*ISO*) at  $15 \mu\text{m}$  and radio images (Garrett et al. 2001). Several examples of serendipitously selected high-redshift SMGs with known redshifts are also shown, including some gravitationally lensed examples. The values of  $T_d$  and  $L$  inferred from these samples and their uncertainties were discussed by BBC03, and have now been updated for Fig. 1. We now also plot the inferred  $T_d$  and  $L$  values derived for the Chapman et al. (2003b, 2004a) sample of 73 SMGs with spectroscopic redshifts.

Following BBC03, values of  $T_d$  and  $L$  are derived assuming a modified blackbody SED with a single dust temperature, and a dust emissivity index  $\beta = 1.5$ , which is extrapolated with a continuous gradient to a power-law  $f_\nu \propto \nu^\alpha$  at frequencies above which the gradient of the blackbody spectrum is steeper than this power law. The value of  $\alpha = -1.7$  is used here, because it provides a good description of the shape of  $15\text{-}\mu\text{m}$  source counts based on the form of evolution inferred for the SMGs (Blain et al. 2002). More information about the range of values of this parameter awaits observations with the *Spitzer Space Telescope*.<sup>3</sup> Arp 220 has amongst the steepest indices known with  $\alpha = -2.9$  (BBC03).

All the galaxy samples shown in Fig. 1 have been fitted using the same function, so the derived luminosities and temperatures for each sample should be directly comparable. This three-parameter ( $T_d$ ,  $\alpha$ ,  $\beta$ ) model is the simplest that can describe the data adequately, and  $T_d$  is the most important parameter (BBC03). To emphasize, the value of  $T_d$  does not necessarily reflect the true phys-

ical temperature of most of the dust in the galaxy, but does provide a good description of the general properties of the SED.

When fitting the SEDs, we assume that the low-redshift radio–far-IR flux density correlation (Condon 1992), resulting from the fact that high-mass stars are the common power source for both synchrotron radio emission via supernovae shock acceleration, and far-IR dust emission via absorbed blue/UV stellar light, applies to the Chapman et al. (2003b, 2004a) galaxies. Under this assumption, we can determine a temperature  $T_d$  to describe the SED from just two data points at 1.4 GHz and  $850 \mu\text{m}$ . If there are systematic changes in the radio–far-IR flux density ratio or its scatter with redshift, then these values will be in error. So far there is no evidence for evolution in the form of the far-IR–radio correlation (Garrett et al. 2001). Information to test the inferred SEDs could be provided by difficult-to-obtain shorter submillimeter flux density measurements in the 350- and  $450\text{-}\mu\text{m}$  atmospheric windows, or from space-borne far-IR data. So far, archival  $450\text{-}\mu\text{m}$  SCUBA measurements at the James Clerk Maxwell Telescope (Smail et al. 2002) and new  $350\text{-}\mu\text{m}$  measurements using the Caltech Submillimeter Observatory (Mauna Kea)’s SHARC-2 camera by Kovacs et al. (2004) for about 10 SMGs show no major discrepancy as compared with the radio–submillimeter result: the dust temperatures inferred from the measured submillimeter color between 350 and  $850 \mu\text{m}$  are consistent with those derived using the far-IR–radio correlation (Fig. 1) to within the errors.

The presence of an active galactic nucleus (AGN) might be expected to boost the radio flux density, leading to an overestimate of  $T_d$  (Yun, Reddy & Condon 2001). This is clearly the case in only 3 out of 73 galaxies in this sample, for which very high dust temperatures and luminosities are inferred. Where X-ray observations are available for the Chapman et al. sample, the results are inconsistent with a large fraction of Compton-thin AGNs (Alexander et al. 2004).

Note that, as discussed by BBC03, the addition of more continuum data points reduces the uncertainties in the fits, but does not break the basic redshift–temperature degeneracy for SED fits.

The size of the uncertainties on the estimated parameters  $L$  and  $T_d$  for the Chapman et al. sources are highlighted in Fig. 2 along with their redshifts: the uncertainties on the estimates for the other samples were discussed by BBC03. The individual uncertainty on any determination is comparable to the extent of the  $L$ – $T_d$  parameter space spanned by the Chapman et al. sample. We also highlight the selection criteria for the SMGs in Fig. 2. The error bars to the  $T_d$  are assigned by fitting SED templates to the colors of observed SMGs, using a maximum-likelihood estimator combined with broad priors, and without imposing any condition on luminosity. The error bars in luminosity are derived from the range of luminosity values for which  $\chi^2 < 4$  for the two data points as the temperature moves away from the best-fitting value. Examples of correlations between fitted values of  $L$  and  $T_d$  are shown by a joint simple  $\chi^2$  fit to the flux density data for two typical SMGs in Fig. 3.

## 3. SELECTION EFFECTS

<sup>3</sup> <http://ssc.spitzer.caltech.edu>

The different galaxy samples occupy somewhat different regions of the  $L$ - $T_d$  plane shown in Fig. 1. Part of this separation is due to their distinct selection criteria. The low-redshift *IRAS* galaxies occupy a relatively well-defined strip, whether their SEDs are determined from either far-IR-submillimeter colors (open squares; Dunne et al. 2000) or from radio-far-IR template fitting (solid lines; Chapman et al. 2003a). The more distant Stanford et al. (2000) sample includes galaxies with greater luminosities, and with typically higher and more scattered temperatures. These two samples match well at intermediate luminosities,  $L \simeq 10^{12} L_\odot$ , for which typical temperatures of about 40 K are determined. It is likely that both of these samples are biased against galaxies with cooler dust temperatures, because their inclusion requires a detection at the relatively short observed wavelength of  $60 \mu\text{m}$ . This corresponds to an even shorter restframe wavelength of about  $45 \mu\text{m}$  for the typical galaxy in the Stanford et al. sample. A few faint galaxies selected jointly at radio and mid-IR wavelengths are found to have SEDs consistent with lower temperatures (Garrett et al. 2001; see also Chapman et al. 2002). The new, large and more accurately defined Chapman et al. (2004a) SMG sample (roughly detected at a restframe wavelength of  $250 \mu\text{m}$ ) also is systematically cooler, with a locus of points that lie at significantly lower temperatures than the trend of the *IRAS*-selected samples in the  $L$ - $T_d$  plane shown in Figs 1 & 2.

The track of the  $L$ - $T_d$  distribution of SMG points in Fig. 2 appears to be relatively tight, but this does not necessarily reflect a tight intrinsic scatter in the properties of the SMGs. Rather, the shape of this distribution is determined mainly by the condition of a detectable submillimeter-wave flux density, as shown by the dashed curves that trace the limits to detection for a 5-mJy  $850\text{-}\mu\text{m}$  source in the Chapman et al. (2004a) SMG sample at a variety of redshifts in Fig. 2. Thus, it is impossible to select SMGs in the high- $T_d$ -low- $L$  region shown in the figures at any redshift in existing submillimeter-wave surveys. In a deeper survey, as will be possible with the Atacama Large Millimeter Array (ALMA; Wootten et al. 2001) the region of the parameter space that can be probed will expand, and many high-redshift galaxies will then probably be found in this region. The nature of high-redshift galaxies means that there are many possible explanations for why they avoid the low-luminosity-high-temperature region of the  $L$ - $T_d$  parameter space. They could have systematically different dust grain properties and spatial distributions of dust as compared with their more luminous companions, or they could be dusty galaxies at the start or end of a burst of enhanced star-formation/AGN activity, either brightening from or fading into the distribution of much more normal quiescent galaxies. Note that regular star-forming Lyman-break galaxies (LBGs; Steidel et al. 2004) will be found somewhere in the  $L$ - $T_d$  plane at high redshifts (Fig. 2d). By detecting their lower far-IR luminosities using ALMA it should be possible to understand the currently ambiguous relationship between the LBGs and SMGs in more detail.

The corresponding conditions for radio detection at 1.4-GHz – that a galaxy must exceed a flux density of about  $30 \mu\text{Jy}$  is also shown in Fig. 2. The shape of the radio selection function is much less sensitive to tempera-

ture, depending much more strongly on luminosity, with a more intuitive redshift dependence.

The absence of points at high-luminosities in the  $L$ - $T_d$  diagram reflects the steep high-luminosity cutoff of the luminosity function of dusty galaxies – there are few very luminous objects to find. Note that the observed strong luminosity evolution of dusty galaxies by a factor  $(1+z)^\gamma$  with  $\gamma \simeq 4$  for  $z < 2$  (Blain et al. 1999), is implicit in the results shown for different redshift ranges in Fig. 2. Very luminous galaxies are not represented in large numbers in the Stanford et al. sample at  $z \sim 0.5$ , yet are abundant in the SMG sample at  $z \simeq 2.5$ .

Chapman et al. (2004a) found wide discrepancies while comparing the scatter in the radio-submillimeter flux ratios for SMGs with redshifts to the ratio expected assuming the updated Carilli–Yun 1.4-GHz– $850\text{-}\mu\text{m}$  redshift estimator (Yun & Carilli 2002). The range of dust temperatures for SMGs shown in Fig. 2 is spread over a factor of at least 1.4 for SMGs with  $L \simeq 10^{13} L_\odot$ . This implies a radio-submillimeter-far-IR photometric redshift accuracy no better than  $\Delta z \simeq 1$  based on the temperature-redshift degeneracy (BBC03) for the typical SMG spectroscopic redshift  $z \sim 2.5$ : this is in marked contrast to recent claims of much more accurate photometric redshifts by Aretxaga et al. (2003). The presence of hotter dusty galaxies at slightly lower luminosities in the Stanford et al. (2000) sample (Fig. 1) hints that photometric redshift errors could be even larger if SMGs were selected down to deeper submillimeter flux density limits. Photometric redshift techniques at shorter near- and mid-IR wavelengths offer better hope of progress, either using redshifted polycyclic aromatic hydrocarbon (PAH)/silicate dust grain absorption and emission features, or stellar spectral features (Simpson & Eisenhardt 1999; Sawicki 2002; Efstathiou & Rowan-Robinson 2003). Regular multi-band near-IR, optical, UV photometric redshift techniques also hold promise, as many SMGs have the expected optical colors for their spectroscopic redshift (Chapman et al. 2004a), despite having far-IR luminosities that are almost impossible to predict from the optical data. Nevertheless, accurate positions, perhaps from radio or ALMA observations, are still necessary in order to confirm that a particular faint galaxy with a photometric redshift really is the counterpart to a particular SMG.

There is almost no overlap in physical properties between well-studied low-redshift *IRAS* galaxies and the existing catalogs of SMGs, as shown in Figs 1 & 4. These classes of galaxies occupy totally disjoint regions of the  $L$ - $T_d$  parameter space, being separated by a factor of 30% in temperature at comparable luminosities, and by a factor of 10 in luminosity at comparable temperatures. In part this is a selection effect, imposed by the requirement of a  $850\text{-}\mu\text{m}$  flux density in excess of 5 mJy at low redshifts and/or luminosities, as shown in Fig. 2. However, the lack of overlap in the figure could also be a real astrophysical effect, perhaps reflecting either a more diffuse distribution of dust and stars or a lower typical interstellar medium metallicity in the high-redshift SMGs as compared with the *IRAS* galaxies. Spatially-resolved imaging of the radio, submillimeter or far-IR emission from these galaxies will be necessary to reveal the true relationship between these populations, its causes and the relative astrophysics of the *IRAS* and SMG galaxy

populations.

We emphasize that spectroscopic redshifts for SMGs are essential to draw all these conclusions: without them reliable temperature and thus luminosity information cannot be derived.

#### 4. NEW POPULATIONS

A significant fraction ( $\simeq 50\%$ ) of the SMG population with  $850\text{-}\mu\text{m}$  flux densities in excess of  $5\text{ mJy}$  are included in the Chapman et al. (2004a) redshift sample (Fig. 2). Unless there is a significant systematic shift in the SEDs of SMGs at fainter flux densities ( $\simeq 1\text{ mJy}$ ), then slightly fainter, less luminous SMGs will typically populate the region of Fig. 1 that lies between the existing SMG samples and the Dunne et al. (2000) low-redshift *IRAS* galaxies, providing a smooth distribution in luminosity between the extremely luminous high-redshift galaxies and more ordinary local dusty galaxies. These fainter SMGs at moderate and high redshifts will be hard to detect at submillimeter wavelengths prior to the commissioning of ALMA.

High-redshift dusty galaxies with fainter  $850\text{-}\mu\text{m}$  flux densities may have luminosities similar to those of known SMGs, but higher temperatures. These would be an important class of objects, both very luminous and hotter than any population detected so far (Fig. 1). The *IRAS* survey is not deep enough to find such galaxies (Stanford et al. 2000), and small *ISO* samples do not appear to detect them in large numbers (Garrett et al. 2001; Franceschini et al. 2003). The deepest *ISO*  $15\text{-}\mu\text{m}$  images (Altieri et al. 1999; Metcalfe et al. 2003) may include some examples, but redshifts, and supporting deep submillimeter and radio data are not common for this population.

With  $T_d \simeq 60\text{ K}$  and  $L \simeq 10^{13} L_\odot$  such hot galaxies at  $z \simeq 2\text{--}3$  could be detected in current deep radio surveys (Fig. 2), but not in existing submillimeter surveys. A factor of 10 increase in submillimeter sensitivity is required to probe this region of the  $L\text{--}T_d$  diagram. Because confusion noise sets the  $850\text{-}\mu\text{m}$  sensitivity limit at about  $2\text{ mJy}$  in field galaxy surveys using current telescopes (Blain et al. 2002), higher angular resolution or a large gravitational lensing magnification, not just longer integrations, would be necessary.

Optical spectra taken in parallel to Chapman et al.'s SMG redshift survey have provided redshifts for many optically faint galaxies that have weak radio detections but no submillimeter emission (Chapman et al. 2004b). These galaxies' optical spectral properties are similar to those of high-redshift SMGs, without signs of powerful AGN, so it is plausible to suggest that their radio emission is produced by star formation. These optically faint galaxies are excellent candidates for a hotter, high-redshift, dust-enshrouded galaxy population, which cannot be detected in submillimeter surveys owing to the galaxies' high dust temperatures. The surface densities of these galaxies are comparable to those of the SMGs, so a survey covering just a few tenths of a square degree should find a statistical sample of several tens.

Such a population of galaxies would generate background radiation intensity in addition to that from the known SMGs and their fainter counterparts. The extra intensity that they contribute would mostly increase the background intensity at wavelengths shorter than about

$200\text{ }\mu\text{m}$ , where the background reported by Schlegel, Finkbeiner & Davis (1998) is underpredicted both by models of the evolution of SMGs (Blain et al. 1999, 2002), and by summing over the flux and surface densities reported for SMGs and their fainter dusty counterparts. Possible sources of  $200\text{-}\mu\text{m}$  background radiation are discussed by Blain & Phillips (2002): a 50% increase in the intensity of background radiation above that accounted for by extrapolating the known SMG population is possible at about  $100\text{ }\mu\text{m}$ , and could be due to a hotter high-redshift population of dusty galaxies.

The known selection effects for existing submillimeter and far-IR surveys, observational hints at a spectroscopically similar, but submillimeter-faint, population of high-redshift radio source, and the intensity of the  $100\text{--}200\text{-}\mu\text{m}$  extragalactic background radiation, are all consistent with the existence of a proposed population of hot high-redshift dusty galaxies. To be certain that we have revealed this population it is necessary to probe deeper into the luminosity function of dusty galaxies at high redshifts, an opportunity that is available most easily at shorter mid-IR wavelengths.

#### 5. SPITZER PROBES OF NEW POPULATIONS

The recently launched *Spitzer* offers excellent sensitivity and an unprecedentedly large field of view at mid and far-IR wavelengths. While it is still not absolutely clear how deep *Spitzer* can integrate before being limited by confusion noise, it will certainly produce much better images of the far-IR sky than any previous mission. Fig. 4 shows the region of the  $L\text{--}T_d$  plane that *Spitzer* will probe to the estimated confusion limits (Blain et al. 2002) at various wavelengths. Deep *Spitzer* observations can thus investigate the whole of the unprobed region of the  $L\text{--}T_d$  plane near  $60\text{ K}$  and  $10^{13} L_\odot$  at  $24\text{-}\mu\text{m}$ . In the unlikely event that a source confusion limit brighter than  $0.1\text{ mJy}$  prevents *Spitzer* from reaching this depth, then the larger  $2.5\text{-m}$  aperture SOFIA<sup>4</sup> airborne observatory will certainly be able to probe this region of the  $L\text{--}T_d$  plane in very long exposures.

The  $24\text{-}\mu\text{m}$  flux density expected for a distant galaxy as a function of  $T_d$  and  $L$  depends most strongly on the value of the  $\alpha$  parameter that describes the mid-IR SED. However, increasing or decreasing  $\alpha$  by  $0.5$  leads to less than a factor of two change in the predicted far-IR luminosity at  $24\text{-}\mu\text{m}$  expected from a galaxy at redshift  $z = 2.5$  for  $T_d > 40\text{ K}$ . If an extreme value of  $\alpha = -2.9$  (representative of the steepest known mid-IR SED in Arp 220) is assumed, then only galaxy luminosities that are a factor of 5 times higher than the limits shown in Fig. 4 can be probed using a  $24\text{-}\mu\text{m}$  observation to a certain flux density limit. Hence, even for the most extreme SED, a *Spitzer*  $24\text{-}\mu\text{m}$  survey can still access the unexplored region of the  $L\text{--}T_d$  parameter space highlighted in Fig. 4 for galaxies at  $z \simeq 2.5$ .

At wavelengths longer than about  $100\text{ }\mu\text{m}$ , confusion noise from faint undetected galaxies makes it difficult to probe the unexplored region at high redshifts unless the telescope used has an aperture greater than of order  $3\text{-m}$ . Hence, to sample the full range of known high-redshift galaxy SEDs near their restframe emission peak will require a next-generation  $10\text{-m}$ -class far-IR telescope, such

<sup>4</sup> <http://sofia.arc.nasa.gov>

as the NASA *SAFIR* vision mission.<sup>5</sup>

Its sensitivity to less-luminous and hotter galaxies at lower redshifts will also ensure that *Spitzer* can be used to reveal whether the absence of low-luminosity, hot, relatively low-redshift galaxies in Fig. 4 reflects a real upper limit to the luminosity-weighted dust temperature in galaxies, or whether it is a selection effect brought about by insufficient sensitivity in existing surveys. Note that because the line defining the  $24\text{-}\mu\text{m}$  selection condition is predicted to be orthogonal to the track of the existing data points through Fig. 4, *Spitzer* observations will be sensitive to any high-redshift galaxies with luminosities in the range  $10^{11}\text{--}10^{12} L_{\odot}$ , and temperatures  $T_d > 50\text{ K}$ . Hence, they could readily test whether the upper temperature limit to the SEDs in existing samples is a real astrophysical result or a selection effect.

A further benefit of the great sensitivity of *Spitzer* is its ability to detect any luminous galaxies that lie on the cold side of the SMG track in Fig. 4 (e.g. Chapman et al. 2002). The details of the detectability of cooler galaxies at the short rest wavelength of  $24\text{ }\mu\text{m}$  are uncertain, and will remain so until the release of the first *Spitzer* data in mid-2004. Although such cold luminous galaxies should be detectable in existing submillimeter surveys, the much larger sky area that should be covered by *Spitzer* – of the order of  $100\text{ deg}^2$  as compared with the  $0.5\text{--}1\text{ deg}^2$  covered by all existing deep mm and submillimeter-wave surveys – will yield a larger number of potential examples. Deep *Spitzer* images of SMG fields will also provide a direct test of the SEDs assumed for the SMGs based on the far-IR–radio correlation when placing the SMGs on the  $L\text{--}T_d$  plane in Fig. 1, and thus will test the evolution of this correlation. Note that to identify the most interesting sources among the huge crop of *Spitzer* detections, deep radio and submillimeter data will still be very valuable, to provide accurate positions and SED/temperature limits respectively.

If *Spitzer* detects faint high-redshift  $\mu\text{Jy}$  radio galaxies and confirms that they lie in the unexplored region of the  $L\text{--}T_d$  plane (Fig. 4), then we will have a full measure of the scatter in the SEDs/temperatures of high-redshift luminous dusty galaxies. If not, then we will have found a new population of distant radio-selected galaxies without obvious AGN signatures (Chapman et al. 2004b; Alexan-

der et al. 2004). These galaxies would have to lie on the radio-loud side of the low-redshift radio–far-IR correlation. This new class of galaxies could be either X-ray and optically faint, dust-enshrouded, Compton-thick AGNs, or distant star-forming galaxies with anomalously powerful radio emission, which are found only at the 1% level in low-redshift samples (Yun et al. 2001).

## 6. CONCLUSIONS

The recent acquisition of a large sample of SMG redshifts provides the opportunity to constrain the SEDs of the most luminous ( $> 10^{12} L_{\odot}$ ) high-redshift galaxies. It is now reasonably certain that the typical high-redshift SMGs selected at  $850\text{-}\mu\text{m}$  are systematically cooler than local dusty galaxies of comparable luminosity, and are thus without direct low-redshift analogs. The scatter in their dust temperatures is about 50%, sufficient to introduce a  $\sim 30\% \text{--} 40\%$  uncertainty in any photometric redshifts derived from far-IR, submillimeter, or radio photometry, no matter how accurate. The true scatter of the dust temperatures in high-redshift dusty galaxies certainly could be still greater, but hotter examples cannot be selected by existing submillimeter surveys. Faint radio galaxies that are undetected in the submillimeter, but whose optical properties are like those of the SMGs hint at the existence of a hotter population, with luminosities  $L \simeq 10^{13} L_{\odot}$  and temperatures  $T_d \simeq 60\text{ K}$ . These galaxies would produce a luminosity density comparable to that of the existing populations of SMGs. The deepest forthcoming mid-IR *Spitzer* surveys should soon confirm whether this population exists, while providing a complete inventory of the range of SEDs present in high-redshift dusty galaxies in fields that have excellent supporting long-wavelength data.

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<sup>5</sup> <http://safir.gsfc.nasa.gov>

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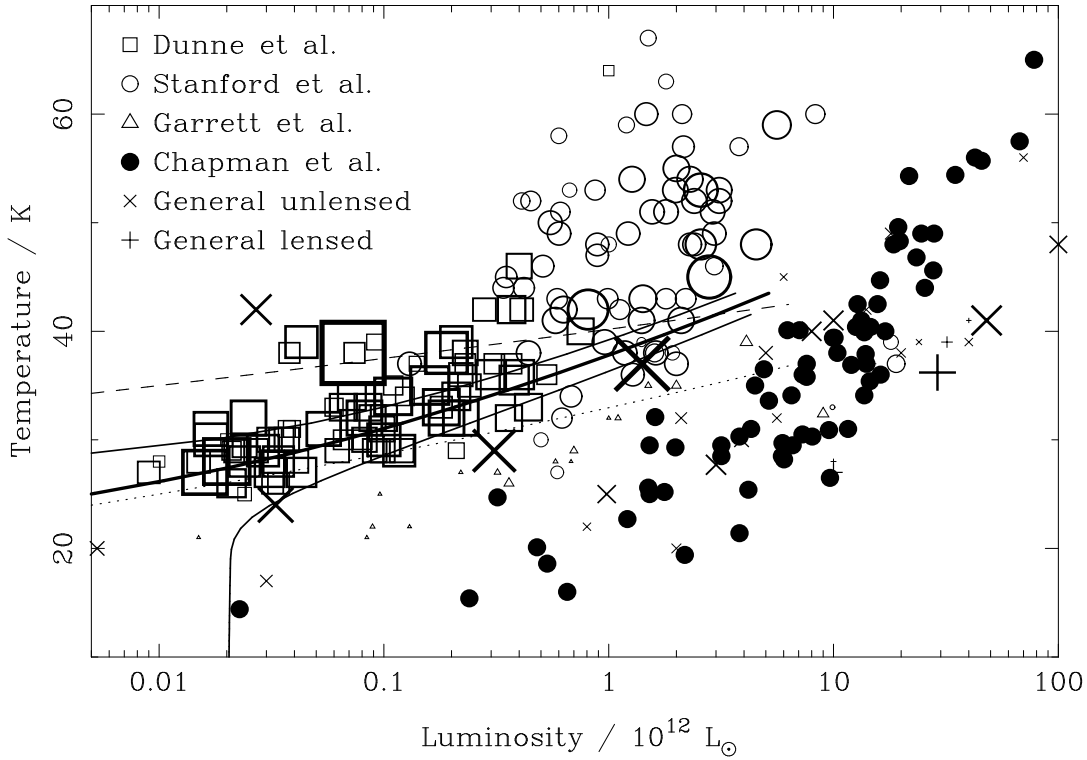


FIG. 1.— Range of luminosity  $L$  and temperature  $T_d$  values determined for well-studied dusty galaxies at a variety of redshifts. Open squares, low-redshift *IRAS* galaxies (Dunne et al. 2000); open circles, moderate-redshift very luminous *IRAS* galaxies (Stanford et al. 2000); open triangles, high-redshift *ISO* galaxies (Garrett et al. 2001); filled circles, spectroscopically identified SMGs (Chapman et al. 2003b, 2004a). Crosses and plus signs show galaxies with well-determined SEDs from a wide variety of sources (including SCUBA and *ISO* surveys). Crosses represent a selection of gravitational lenses, while plus signs represent unlensed galaxies (for both see BBC03); and spectroscopically identified SMGs – filled circles (Chapman et al. 2003, 2004a). The sample represented by diagonal crosses includes M82, the Milky Way, NGC 958 and Arp 220, which are shown by the largest crosses between  $2 \times 10^{10} L_\odot$  and  $1.6 \times 10^{12} L_\odot$  respectively. For the non-Chapman samples larger symbols reflect more accurate determinations: see BBC03 for a description of the errors for these samples. See Fig. 2 for uncertainties in the estimates for the Chapman et al. sample, for which all symbols are the same size. The thick solid line shows the result derived by Chapman et al. (2003a) for the  $L$ – $T_d$  values of low-redshift *IRAS* galaxies. The interquartile range for this sample is bracketed by the two thinner solid lines, the separation of which agrees well with the range of properties of the Dunne et al. sample. The dashed and dotted lines show the fits obtained to merging and quiescent low-redshift *IRAS* galaxy data respectively by Barnard (2002).

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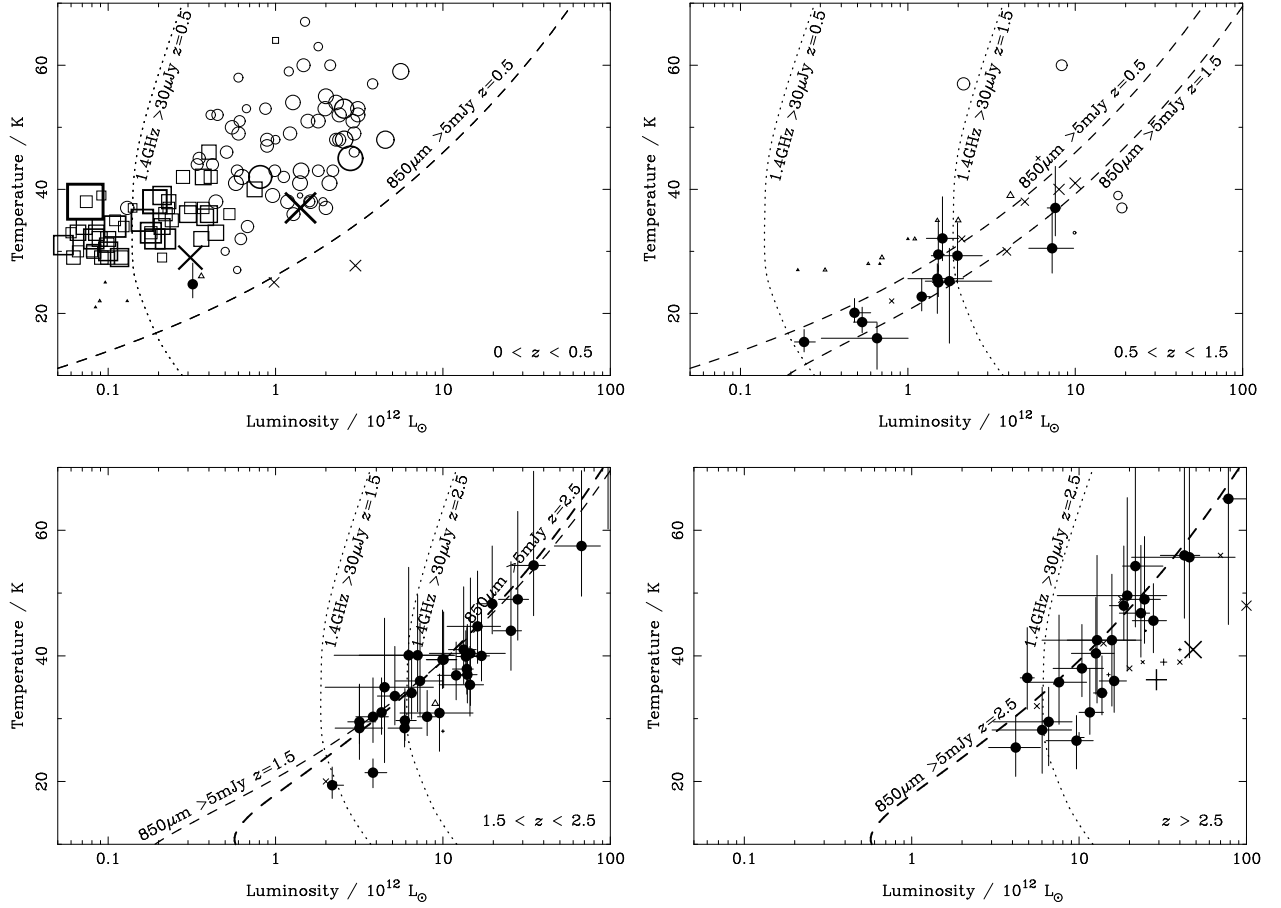


FIG. 2.— SED parameters for the galaxies shown in Fig.1 divided by redshift range, and the errors on the parameters fitted to the Chapman et al. (2003b, 2004a) sample, symbols are as in Fig.1. The selection effects that limit the SED parameters for galaxies in this sample are represented by the lines at submillimeter and radio wavelengths for the labeled redshifts. Galaxies can be detected to the high-luminosity side of each line. There is a trend for the most luminous galaxies to be at the highest redshifts, reflecting the strong evolution of the luminosity function of the dust-enshrouded galaxy population. Nevertheless, note that broad ranges of luminosity, and more importantly temperature, are sampled in each redshift interval regardless of the selection effects.

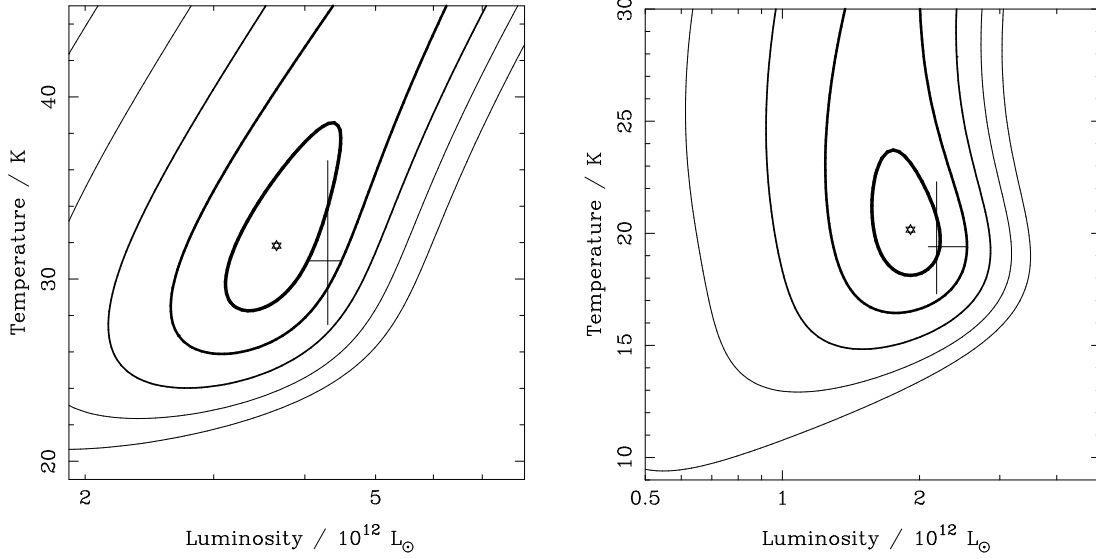


FIG. 3.— Examples of the uncertainties in the SED fit obtained for two typical radio-submillimeter galaxies in the HDF field. Left: SMMJ123707.21+621408.1, No. 242; right: right is SMMJ123721.8+621035.3, No. 378) from Chapman et al. (2004a), at  $z = 2.48$  and 1.51 respectively). The error bars match the results plotted in Fig. 2, and are determined by making a full maximum-likelihood fit to the temperature  $T_d$  for an SED of arbitrary luminosity and then finding the range of best-fitting values of  $L$  that have a value of  $\chi^2 < 4$  at that value of  $T_d$ . The contours show reduced  $\chi^2$  values of 1, 4, 9, 16 and 25 derived directly for comparison. The  $L$ - $T_d$  values are consistent, but slightly distinct, reflecting the different fitting procedures. The minimum  $\chi^2$  value is denoted by the star. Note that the extent of the contours in the temperature direction can be reduced by adding any data from *Spitzer* mid- or far-IR observations.

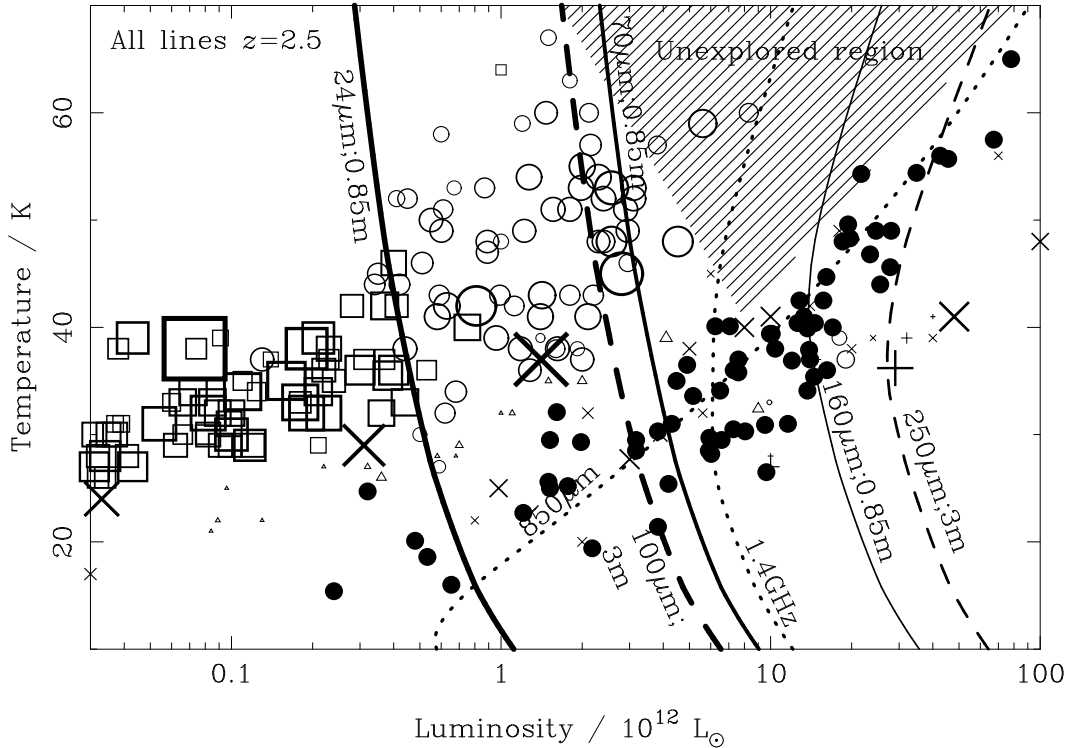


FIG. 4.— Full range of  $L$ - $T_d$  values determined for dusty galaxies (see Fig. 1). The lines show the limits for selecting galaxies in surveys close to the confusion limit for a 0.85-m aperture telescope like *Spitzer* and a 3-m-class telescope like *Herschel* or SOFIA, for a galaxy at redshift  $z = 2.5$ , typical of the identified SMGs. The solid lines show the limits of *Spitzer* at 24  $\mu\text{m}$  (thick lines; 0.1 mJy), 70  $\mu\text{m}$  (medium lines; 5 mJy) and 160  $\mu\text{m}$  (thin lines; 80 mJy). The dashed lines represent the limits of a 3-m aperture telescope at 250  $\mu\text{m}$  (thin lines; 70 mJy), and 100  $\mu\text{m}$  (thick lines; 1.5 mJy). The selection limits in the existing Chapman et al. samples (Fig. 2) are shown by the dotted lines. Galaxies to the high- $L$  side of all the lines can be detected. Reaching the unexplored region to find ultraluminous ( $L \sim 10^{13} L_\odot$ ) galaxies at  $T_d \simeq 60$  K requires *Spitzer* observations at 24  $\mu\text{m}$  or an aperture larger than about 3 m at observing wavelengths longer than 100  $\mu\text{m}$ . To probe a significant part of the unexplored region of the diagram at submillimeter wavelengths would require a survey depth of order 0.1 mJy at 850  $\mu\text{m}$  with ALMA.